

Planning and Logistics for the In-Field Demonstration of NASA's Habitat Demonstration Unit (HDU) Pressurized Excursion Module (PEM) at Desert RATS 2010

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Abstract

This paper describes the construction, assembly, subsystem integration, transportation, and field testing operations associated with the Habitat Demonstration Unit (HDU) Pressurized Excursion Module (PEM) and discusses lessons learned. In a one-year period beginning summer 2009, a tightly scheduled design-develop-build process was utilized by a small NASA “tiger team” to produce the functional HDU-PEM prototype in time to participate in the 2010 Desert Research and Technology Studies (Desert RATS) field campaign. The process required the coordination of multiple teams, subcontractors, facility management and safety staff. It also required a well-choreographed material handling and transportation process to deliver the finished product from the NASA-Johnson Space Center facilities to the remote Arizona desert locations of the field test. Significant findings of this paper include the team’s greater understanding of the HDU-PEM’s many integration issues and the in-field training the team acquired which will enable the implementation of the next-generation of improvements and development of high-fidelity field operations in a harsh environment. The Desert RATS analog environment is being promoted by NASA as an efficient means to design, build, and integrate multiple technologies in a mission architecture context, with the eventual goal of evolving the technologies into robust flight hardware systems. The HDU-PEM in-field demonstration at Desert RATS 2010 provided a validation process for the integration team, which has already begun to retool for the 2011 field tests that require an adapted architecture.

I. Background

THE Habitat Demonstration Unit (HDU) Project was conceived in the spring of 2009 as a means to develop medium-fidelity, functional habitat modules via a rapid-prototyping process for the purpose of supporting planetary surface and deep space analog testing scenarios. It was envisioned that these habitat modules could be used to assess not only habitability aspects of future space exploration habitats but operational aspects as well. The first architectural configuration chosen to be represented by the HDU Project was the Pressurized Excursion Module (PEM), which was one of the habitable elements of NASA’s Lunar Architecture Team (LAT) scenario known as LAT 12.1¹ (see Fig. 1). The PEM had been conceived by the LAT as a 5-meter diameter vertical axis cylinder with docking hatches and a deployable airlock (see Fig. 2). Driven by these basic requirements, the conceptual design for

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the HDU Project's first-generation shell consisted of a 5-meter diameter vertical axis cylinder with a domed top and bottom constructed of eight wedge sections. The shell had four rectangular hatches spaced at 90 degree intervals along the cylindrical outer wall of the shell (corresponding to the LAT 12.1 architectural concept for the Pressurized Core Module) and a circular hatch at the center of the upper dome for access to a future upper deck loft. Flooring was included in the design both inside the shell and on top of it, forming an upper deck for the anticipated loft addition. The entire HDU shell sat on a square support cradle which had four leveling legs and associated foot pads. An attached Airlock module was included in the conceptual design.



Figure 1. Artist's concept of LAT 12.1 mission architecture.

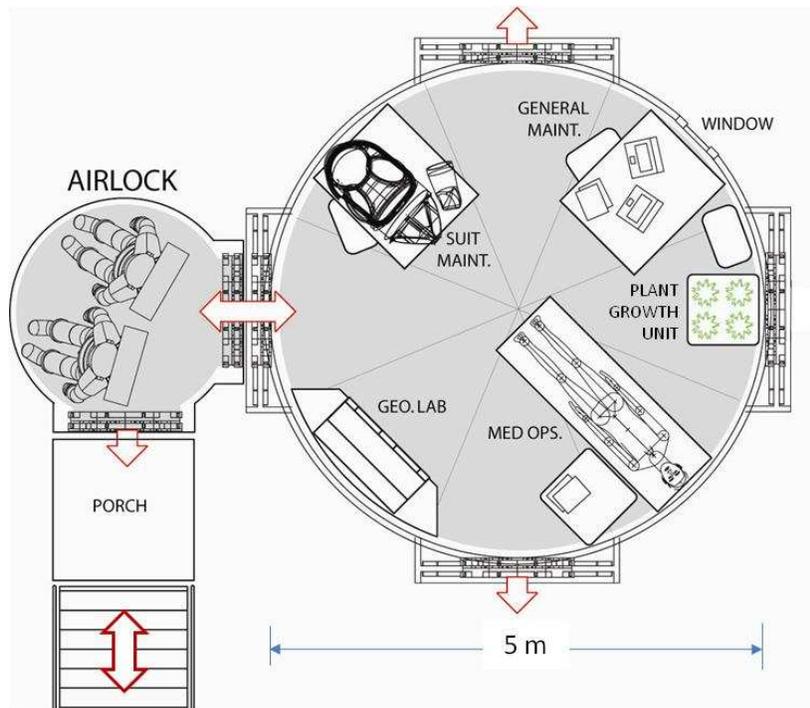


Figure 2. Plan view of HDU-PEM with attached Airlock module.

II. Construction and Assembly

The eight sections of the HDU shell, which were constructed by a team at NASA's Langley Research Center (LaRC), each consisted of a pair of steel ribs molded into a shell of resin impregnated fiberglass. The eight sections were shipped to JSC via flatbed truck in two separate shipments of four sections each—the first in December of 2009 and the second in January of 2010. The first four segments—each approximately 45 degree wedges—were joined together upon their arrival at JSC to assess the general alignment of the multi-segment assembly (see Fig. 3). Upon measurement of the resulting assembly, it was decided to construct one of the remaining four segments in two separate halves, with an overlapping joint. This joint could absorb any angular variances in the final wedged-shaped opening that might result from additive manufacturing variances. The cradle was then assembled in place around the shell and attached to it. Inside, the floor substructure was installed, and the floor panels were laid in place. Similarly, the upper deck flooring substructure and floor panels were also installed. Finally, doors were installed in each of the hatchways. In addition to the HDU assembly activities, the acquisition of an airlock was also critical to the development of the PEM configuration. After weighing several options and driven primarily by budget concerns, the HDU Team chose to re-use a large polyethylene tank which had previously been used as a simple airlock mockup as part of a previous Desert RATS field test. At this point, the basic HDU shell and Airlock were complete and ready for subsystem installation and integration.



Figure 3. HDU shell buildup with four wedge segments (photo by author, 2010).

III. Subsystem Integration

Prior to assembly of the shell, a significant effort had been undertaken to define the various infrastructure subsystems, workstations, and test articles which would be integrated into the HDU shell to configure it as the PEM². From February 2010 through mid-July 2010, all of this hardware was installed, integrated together, and checked out—taking about six weeks longer than originally planned. Part of this delay was caused by the application of the foam insulation to the exterior surfaces of the HDU shell and the Airlock, which prevented all work inside either of the two subelements from occurring for almost three weeks, due to safety and contamination concerns associated with the insulating process. Additionally, one of the most critical integrating subsystems—the avionics subsystem—was suffering significant delays in finalizing the buildup of its two main avionics “boxes.” By the time the decision was made to move the HDU from its assembly facility in JSC's Building 220 to the JSC Rock Yard facility in preparations for integrated dry run testing, not all subsystem integration activities had yet been completed.

IV. Dry Run Testing

The dry run testing scheduled for the Rock Yard was planned for one week in July and one week in August 2010 (see Fig. 4). The purpose of the dry runs was to evaluate the “field readiness” of the elements which were participating in the Desert RATS 2010 field campaign to be conducted over a twenty-six day period from late August through mid-September 2010. The dry runs were also a chance to test various elements and systems in an integrated fashion and to give the crews a chance to familiarize themselves with the operations of the hardware and software systems. For the HDU, one of the crucial operations to be evaluated during the dry run period were the loading and unloading operations associated with the HDU, the Airlock, and all of the ancillary field support equipment. Due to the size and weight of the HDU (over 5 meters in diameter and nearly 12,000 kilograms), a large crane was required to load the HDU with its cradle onto a flatbed trailer at the Building 220 facility and, in turn, unload it at the Rock Yard facility. Fortunately, most of the other ancillary equipment could be loaded onto a



Figure 4. HDU-PEM participating in dry run evaluations at the JSC Rock Yard facility (photo by author, 2010).

separate flat bed truck using only a forklift. After the HDU and Airlock were transported to the Rock Yard, the two were placed onto the simulated terrain, positioned, leveled, and joined together. Once the HDU, Airlock, and all supporting equipment were configured, a portable diesel generator was interfaced to the HDU power subsystem and to the HDU heat pump, providing both power and cooling to the interior of the HDU and Airlock. This was important, due to the fact that several integration items were still unfinished inside the HDU, and it was late July in the hot Houston, Texas, climate. Also integrated with the HDU avionics and communications subsystems was the HDU Command Bus, a reconfigured recreational vehicle formerly used by the U. S. Secret Service as a mobile command post. The Command Bus now served as a portable mission control center for the HDU, housing control and monitoring consoles for key subsystem support personnel. Despite the ongoing testing of its subsystems, the HDU was able to support integrated element testing in the Rock Yard with the two rovers, which repeatedly performed docking and undocking maneuvers with the HDU hatch interfaces—both with and without the Active-Active Mating Adapter (AAMA). Upon successful completion of the Rock Yard dry run testing, the HDU, Airlock, and supporting field equipment were deemed ready for shipment to the analog field test site.

V. Transportation

The HDU—when loaded onto a flat bed trailer—extends well over a meter on either side of the trailer, thus it is classified as a “super wide-load” for transportation across the U. S. highway system (see Fig. 5). Due to various state-to-state travel restrictions on super wide-loads, the HDU’s journey from JSC to the test site in the desert north of Flagstaff, Arizona, takes approximately a week to complete. However, a standard width load, such as the trailer used to ship the ancillary equipment, can make the same trip in less than forty-eight hours. All in all, there were three vehicles involved in transporting HDU assets to the D-RATS test site—two flat bed tractor-trailers and the Command Bus. The first vehicle to depart from JSC was the super wide-load tractor-trailer, which carried the HDU,



Figure 5. The HDU-PEM, classified as a super wide-load payload, arrives by tractor-trailer at SP Mountain, Arizona (photo by author, 2010).

the Airlock, and the heat pump. All three payloads were securely chained to the trailer, and the HDU and Airlock were additionally tarped to protect them from the elements and road debris during the week-long trip. Second to depart was the Command Bus, which was loaded with equipment and supplies for the field test operations and which was driven by two of the HDU field team members. Last to leave—a week later than the first vehicle—was the standard width tractor-trailer, which carried a small shipping container filled with equipment and supplies, the Airlock porch and ramp, a staircase, and two crated power subsystem modules. On the same day the last vehicle departed from JSC, several advance HDU field team members departed from their respective NASA Centers to rendezvous in Arizona.

VI. Field Test Operations

The culmination of all of the HDU Project’s efforts thus far in its relatively short existence was to be the field test operations of the unit at the Desert RATS 2010 field campaign in the Gray Mountain area approximately forty-five minutes north of Flagstaff, Arizona. The first HDU team members arrived at the test site on August 23, 2010, and some of them would not be leaving Arizona until after the last day of the field campaign—September 18, 2010—as the trucks departed the test site with all of the HDU assets loaded aboard.

A. Desert RATS Background

The Desert RATS field test activities have been conducted in various desert locales in the western U. S. for well over a decade. These efforts began humbly as evaluations of space suit mobility systems and gradually grew to support such areas as robotics, unpressurized rovers, pressurized rovers, integrated communications systems, and finally habitat elements. The field team size, which started as a handful of researchers, had grown by the 2010 field campaign to nearly 200 individuals over the course of the three and a half week campaign. Over the past several seasons, the Black Point Lava Flow (BPLF) area near Gray Mountain had become popular because of the abundant presence of interesting geological features with which test crews could conduct actual geological field science operations which were representative of those which would be conducted by future planetary explorers.

B. PEM Testing Objectives

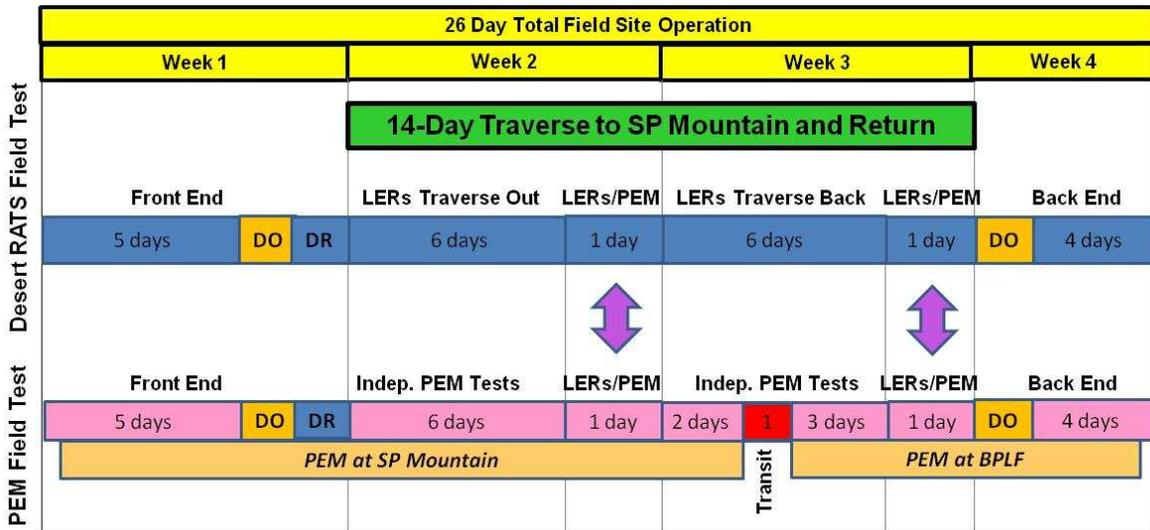
The primary testing objectives for the PEM configuration of the HDU were categorized into three major categories—architectural objectives, hardware objectives, and operational objectives. These objectives flowed down from higher level Desert RATS field campaign objectives, primarily the objective to assess the LAT 12.1 architecture involving the PEM with two rovers on an expeditionary traverse. In turn, lower level objectives relating to the PEM’s workstations, test articles, and infrastructure subsystems flowed down from the PEM’s primary testing objectives. The primary testing objectives are listed in Table I. Likely the most important of these objectives were the collection of the PEM’s general habitability and human factors data, which was primarily gathered from video analysis, support crew observations, and test crew surveys.

Table I. Top-Level Objectives.

Architctural Objectives:	Validate the use of the PEM as described in the LAT 12.1 architecture
Hardware Objectives:	Evaluate the use of the PEM geosciences laboratory in conjunction with sample collection by the rover crews
	Evaluate the use of the EVA maintenance area in the PEM
	Perform a "shake-down" assessment of the integrity of the HDU after the long-haul transportation of the unit to the field site
Operational Objectives:	Evaluate logistics and waste management in conjunction with dual rover operations
	Evaluate the PEM human factors associated with a crew of four while docked to the rovers
	Evaluate the effectiveness of dust mitigation procedures
	Determine the PEM power duty cycle profile

C. Timetable

The timetable of PEM activities at Desert RATS 2010 closely matched that of the overall integrated timeline involving all of the field elements. Figure 6 shows a comparison of the PEM activities with the integrated timeline.



Notes: Front End includes site preparation, delivery, setup, checkout, and dry runs.
 Back End includes Media, VIP, Int'l. Partner activities; Student activities; pack up, loading, and shipment.
 DO = Day Off
 DR = Dry Run

Figure 6. The top-level timeline of activities at the Desert RATS 2010 field campaign.

Both timelines include the field team and hardware shipment arrival, hardware setup, system checkout, and dry run activities which preceded the two-week testing period. Also, both timelines include the media and VIP day, student day, camp tear-down activities, hardware shipment departure, and field team departure. Additionally both include a dedicated day off both pre- and post-testing period. Where the two timelines diverge is primarily in the two-week testing period. Whereas the two rovers and other assets were actively involved in the integrated two-week test, the PEM was only involved at discrete times. As originally planned, the two-week test simulated a traverse from a lunar outpost to a geological site of interest and return, with the rovers conducting geological studies along the way. This translated to seven days outbound and seven days inbound. At day six outbound and at day thirteen inbound, the two rovers were to each dock with the PEM, and the crew was to spend the following day working inside the PEM at the discrete workstations, providing input to the PEM team on the various operations they were performing. Thus, only two of the fourteen integrated test days involved the PEM; the remaining days were available for independent PEM testing and for translation of the PEM from the SP Mountain site to Base Camp at the Black Point Lava Flow site.

D. Deployment

The initial site for placement of the PEM was near SP Mountain, which is located approximately twenty kilometers from Base Camp. The two tractor-trailers were positioned near the predetermined spot for the PEM to be placed, which had been previously selected and marked by an advance team in late April of 2010. A large crane unloaded all of the assets from the trailers and placed them according to the site plan (see Fig. 7). Other assets were delivered and placed by local companies; these included portable toilets and a hand wash station, a diesel generator, a diesel fuel tank, and a portable office constructed from a shipping container. This last asset was required because the Command Bus had developed mechanical problems during its journey, and a substitute portable mission control center was needed from which to base the operation at the SP Mountain site. The PEM and its heat pump were connected to generator power, as was the portable office. All systems were activated and run through a series of checks. It was at this point that a problem was discovered with the heat pump—a critical item for conducting the testing operations in the PEM. En route, the main refrigerant manifold in the heat pump had become damaged, and after extensive assessment was deemed to be unrepairable. Fortunately, a suitable portable air conditioning cart was found at Base Camp which was being used to cool a large portable office. After discussions were held among the affected Desert RATS teams, it was decided that the portable air conditioning cart would be transported to the SP Mountain site for integration with the PEM and that a standard room air conditioner would be purchased locally to provide cooling to the large portable office at Base Camp.



Figure 7. Unloading the PEM (photo by author, 2010).

E. Independent Test Operations

Once all of the assets were made ready to support testing, the independent test operations could begin. Eleven days of the fourteen-day test period were available for independent testing operations. The main objective of the independent testing was to gain experience with the four main PEM workstations—the GeoLab, the Suit Maintenance Workstation, the General Maintenance Workstation, and the Medical Operations Workstation. This experience was to be gained by running various exercises within the PEM with volunteer crewmembers at each of the workstations during the independent testing days. Because of the previous delays associated with integrating all of the subsystems and conducting adequate performance testing during the summer, very little time had been available to gain experience on the workstations prior to going to the field. As a result, there were significant start-up challenges early on with the independent testing activities. Nonetheless, after diligent efforts by the HDU habitability and human factors team members, these testing procedures were smoothed out, and soon usable data

began to be collected on the individual and joint testing of the workstations in the PEM³. In addition to the evaluations of the four workstations, the test articles were also evaluated during the independent test days. Cursory dust mitigation experiments were conducted using electrostatic dust shield and lotus coating technologies. Additionally, the HDU Impact Monitoring System (HIMS) was evaluated by firing pellets at discrete, instrumented regions of the PEM outer shell, simulating micrometeoroid strikes for the purposes of determining the precise locations of the strikes on the PEM's outer hull.

F. Integrated Test Operation

The PEM integrated test operations were conducted similarly to the PEM independent test operations, with the exceptions that the test operations were run more like missions from the Mobile Mission Control Center by actual JSC Missions Operations Directorate personnel and that the crews were composed of the integrated crewmembers who spent most of their seven day missions inside the rovers or performing simulated EVAs. The first scheduled integrated test day was Day 7. The two rover crews of two each had docked previously with the PEM on Day 6 and had spent the night sleeping in their respective rovers (see Fig. 8). During Day 7, the crew was devoted to



Figure 8. HDU-PEM with dual rover docking at SP Mountain, Arizona (NASA photo, 2010).

performing operations within the PEM that would help to assess functionality of the four workstations, similar to the evaluations made by the volunteer crews during the independent testing operations (see Fig. 9) The crews rotated from workstation to workstation throughout the day, each receiving a chance to interact with each workstation by performing a representative activity. Since the PEM is primarily a work area and has no galley or hygiene facilities, the crewmembers ate their breakfast and lunch in their respective rovers and performed hygiene functions in the rovers as well. After Day 7, the first set of rover crews were to be changed out with the second set of rover crews for the traverse back to Base Camp on Days 8 through 13, with Day 14 to be the “PEM Day.” However, these plans changed slightly when inclement weather rolled through on Day 8, negating rover operations. It was at this point that the Desert RATS Mission Management Team decided to keep the rovers docked to the PEM and have the new set of crewmembers perform a half-day of PEM activities on Day 8, traverse back to Base Camp on Days 9 through 14, and perform a final half-day of PEM activities on the afternoon of Day 14.



Figure 9. Crewmembers performing tasks at workstations in the HDU-PEM (NASA photo, 2010).

G. Moving the HDU-PEM

Due to the fact that the HDU-PEM was required for rendezvous with the rovers at both the SP Mountain destination of the rover traverse and at the return to the Base Camp “lunar outpost,” it needed to be moved at sometime between Day 9 and Day 13. Day 10 was selected as the HDU PEM moving day. On Day 9, the second half of the day was spent disassembling the field camp at the SP Mountain site and packing up all equipment and supplies. On the morning of Day 10, two flat-bed tractor-trailers and the large crane used previously for unloading arrived at the field camp site. The crane, aided by a rented forklift, loaded all NASA assets aboard the two trucks, and then left the site en route to the unloading site. The two tractor-trailers then drove the short distance up the road to the Black Point Lava Flow Base Camp where the awaiting crane unloaded all the NASA assets a short distance south of the main Base Camp tent. In parallel, the rented toilets, handwash stations, portable office, and generator were moved to Base Camp by their respective rental companies. Coincidentally, the Command Bus had finally been repaired and had arrived the night before, now joining the rest of the HDU Team’s field assets.

H. Post-Test Activities

After completion of the two-week test period, the HDU field team enjoyed a day off, and then supported two days of outreach activities which included interaction with various media outlets, NASA international partners, other NASA VIPs, and a range of students and educators. Then the HDU assets at Base Camp were deactivated, packed up, prepared for shipment, loaded onto trucks via crane, and shipped back to JSC. The remaining HDU field team members who had flown to Arizona returned to their home NASA Centers. Unfortunately, the Command Bus once again suffered a malfunction shortly after departing the Base Camp area, and its contents had to be reloaded onto a moving truck and driven back to JSC by two of the HDU field team members.

VII. Lessons Learned

During the testing activities at Desert RATS 2010, a running list of “lessons learned” was collected by the HDU field team members, and after completion of the field campaign, these lessons learned were compiled into a database to serve as a guide for the next phase of HDU development and testing. A summary of these HDU lessons learned was presented to a gathering of Desert RATS participants in early December 2010 as part of an effort to allow all of the field campaign teams to learn from the experiences of others and improve the planning and execution of future Desert RATS efforts. This summary is shown in Table II.

Table II. HDU PEM Lessons Learned from Desert RATS 2010.

Category	What went well?	What didn't go well?	Suggestions for Improvement
HDU/PEM	Split team lodging approach (part staying at Cameron, part staying at Flagstaff) offered proximity to both field camps and logistics providers		Other teams may want to consider the split team lodging approach to reduce driving time to field camps (only 12 minutes from Cameron Trading Post to Base Camp)
HDU/PEM	In-field interaction with Mission Operations personnel on Test Days 7, 8, and 14 went very well	Dry-run operations at JSC were severely compromised due to delays in systems integration and checkout testing	Separate the HDU "Test Integration Operations" responsibility into two distinct functions: "Demo Unit Integration" and "Test Operations" and consider having the latter responsibility staffed by Mission Operations personnel
HDU/PEM	Command Bus served well as a command center for the HDU, along with the 20-foot converted shipping container office	Command Bus broke down several times en route to Arizona and in returning to JSC	Use locally rented shipping container office for command center instead of vehicle that needs to be driven across country
HDU/PEM	HDU move from SP Mountain to Base Camp went very well	Moving the HDU during the campaign takes away valuable test time and resources	Design the field test with a single location for the HDU, if possible
HDU/PEM	SP Mountain "outpost" camp worked well as a satellite to Base Camp	Running two camps takes additional resources and complicates coordination	Design the field test with a single camp, if possible
HDU/PEM			Provide agenda/rotation scheme for both VIP and media days so appropriate time can be spent with equal numbers of people
HDU/PEM		Communications that were limited to that which simulated lunar communications	Request more capability for test communication than lunar communication simulation. Anticipate new communications software next year and want to do dry run on its use before field ops.
HDU/PEM - Geolab	As a rapid prototype geological laboratory (design, build, integrate and test in under a year), GeoLab performed successfully. GeoLab success was dependent on collaboration with HDU PEM team		Continue
HDU/PEM - Geolab	The goal to be ready for deployment and participation in Desert RATS provided the focus and drive for a successful test		Continue.
HDU/PEM - Geolab	Mission Operations involvement contributed to GeoLab success; they provided guidelines and commonality for our operations that allowed for a ready extension from Rover Traverse Operations to HDU GeoLab operations. They also provided a critical review of GeoLab operational procedures		

Table II (continued). HDU PEM Lessons Learned from Desert RATS 2010.

Category	What went well?	What didn't go well?	Suggestions for Improvement
HDU/PEM - Geolab	Having GeoLab operations flow from Science team operations was critical to successful testing of the science operation concepts.		To fully utilize the analog environment and let science objectives and science operational constraints drive instrument requirements, we need to devise future tests with strategic science goals in mind, better define operational hypotheses; and contribute to the definition of mission rules for the tests. Additionally, expand the potential field applications.
HDU/PEM - Geolab		Details of critical subsystems (e.g., communications) were not understood and developed until on-site arrival in Arizona.	Better understanding between all parties about the capabilities and constraints of subsystems, with the goal of developing a working solution before deployment
HDU/PEM - Geolab		The communications team was always working on the edge - they need more support. We recognize the extreme difficulty of establishing the communications subsystem, and the endless efforts by the comm team. We note that if we had suffered total comm outage, we would have recovered no GeoLab data, as the crew were untrained and required interactions with supporting science team.	Better support for Communications team.
Human Factors - HDU/PEM		Insufficient number of personnel in field led to inefficiencies in data collection requiring more post-DRATS time to prepare results and schedule conflicts with other Cx customers	Depending on objectives, need minimum of 1 dedicated Human Factors evaluator per habitat module plus 1 dedicated Human Factors data analyst (not including student intern support)
Human Factors - HDU/PEM		Medical workstation only allocates one half height drawer to non-medical life science and has not tested any life science activities due to lack of input from life science community	Life science community must be convinced of importance of participating in DRATS testing
Human Factors - HDU/PEM		Scenario 12.1 PEM layout failed to account for need to resupply the two rovers, resulting in inadequate stowage volume which forced stowage to occupy undesirable locations	Future layouts must better account for full stowage needs, including those imposed by other projects/vehicles
Human Factors - HDU/PEM		PEM diameter "appears" large but in reality created conflicts between adjacent work envelopes	Larger diameter may be needed for flight vehicles

VIII. Post-Desert RATS HDU-PEM Testing

Upon returning to JSC in late September, testing of the HDU-PEM continued in the Building 220 facility. These evaluations included endurance testing of the software and avionics system, a detailed instrumentation assessment, and don/doff testing of mockup space suits in the Airlock using the newly installed suit donning stations. Additionally, an evaluation known as the "incapacitated crewmember scenario" was performed, in which a



Figure 10. A computer model of the HDU in the Deep Space Habitat configuration.

stuffed mockup space suit was translated from the bottom of the Airlock access ramp, up the ramp, over the porch, and into the Airlock using the Airlock winch, which was operated by a suited test subject. After completion of these final PEM test points in late January 2011, reconfiguration activities began in earnest with the HDU to convert it from the PEM configuration to the Deep Space Habitat configuration in support of the Desert RATS 2011 field campaign (see Figure 10)⁴.

IX. Summary

The development of the HDU-PEM—executed at a rapid pace—was completed in time to participate in the Desert RATS 2010 field campaign, which permitted the LAT 12.1 architecture to be more fully evaluated with all major lunar surface elements represented. The HDU Team demonstrated how the HDU-PEM could be efficiently delivered to two separate remote analog sites and be made functional within a very short time. The independent testing conducted in the HDU-PEM paved the way for successful integrated testing activities. Many lessons were learned at multiple stages of the development and testing of the HDU-PEM, and these lessons can be carried forward not only to future configurations of the HDU, but likely to any future analog habitat development effort.

Acknowledgments

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